Using the Moon for MODIS On-orbit Spatial Characterization

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ABSTRACT

The moon is a very stable reference source that has been used for the space-borne sensors' radiometric calibration and/or radiometric stability monitoring. In this paper, we present an approach that uses the sensors' on-orbit lunar observations for their spatial characterization and apply the method to the MODIS instruments that are currently operating onboard NASA EOS Terra and Aqua satellites. Both MODIS instruments perform monthly lunar observations. The spatial characterization results derived from the lunar observations using this algorithm are compared with those obtained from the MODIS Spectro-Radiometric Calibration Assembly (SRCA), which is an on-board calibrator capable of performing spatial characterizations for all MODIS spectral bands. The new approach can be applied to other remote sensing instruments.

Keywords: MODIS, Moon, spatial characterization, BBR, Terra, Aqua

1. INTRODUCTION

The MODerate Resolution Imaging Spectroradiometer (MODIS), one of the key instruments for the NASA's Earth Observing System (EOS), is currently operating on the EOS Terra and Aqua satellites[1-3]. They were launched on December 18, 1999 and May 4, 2002, respectively. MODIS has 36 spectral bands with three different nadir spatial resolutions: 250m for bands 1-2, 500m for bands 3-7, and 1.0km for bands 8-36. Among them, 20 are reflective solar bands (RSBs) and 16 are thermal emissive bands (TEBs). The radiometric calibration of the RSB is performed with an onboard Solar Diffuser (SD) and Solar Diffuser Stability Monitor (SDSM) [4-7] while that of the TEB by an onboard Blackbody (BB)[5,8]. Another onboard calibrator, the Spectro-Radiometric Calibration Assembly (SRCA), is primarily used for the instrument's spatial and spectral characterization[9-11].

Band-to-band registration (BBR) is a key component of the MODIS spatial characterization. The BBR of the MODIS bands can be derived from SRCA spatial mode data[12]. Currently, the measurement of SRCA in spatial mode is performed once every two months for both Terra and Aqua. The SRCA results have shown that the BBR are quite stable for both instruments.

The moon is known to be a very stable radiometric light source for remote sensor's radiometric stability monitoring[13-17]. MODIS views the Moon through its Space View (SV) Port. Since the lunar irradiance strongly depends on the Sun-MODIS-Earth phase angle, we confine the phase angle to be in the region [55^o, 56^o] for MODIS lunar observations. To keep the phase angle in this region, a spacecraft roll maneuver is usually needed for each lunar observation[17]. Both Terra and Aqua MODIS have viewed the Moon approximately monthly since launch. So far, more than 30 and 10 lunar observations have been implemented for Terra and Aqua MODIS, respectively.

The moon is a point light source and thus can be used for spatial characterization of the on-orbit remote sensors. In this paper, an approach is developed to calculate the BBR of the MODIS along both the scan and track directions using lunar observations and applied to Terra MODIS RSBs. The results are compared to those derived from SRCA spatial mode data, showing good agreement. With the new approach, detector-to-detector registration (DDR) for a given band can also be calculated. The results of the DDR are discussed. This approach can also be applied to other remote sensing instruments.

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2. ALGORITHMS

The MODIS views the Moon through its Space View (SV) Port. The size of the SV along the scan direction is approximately 84 pixels of the MODIS 1km bands. The left image in Figure 1 is the lunar image obtained by Terra MODIS on June 18, 2003 within one scan. Because of the pixel over-sampling effect, there is a strong overlap among the MODIS observation swaths of different scans on lunar surface. The overlap causes the MODIS to view the Moon many times in each lunar calibration. The right image in Figure 1 is the lunar image obtained by Terra MODIS's middle detector of B1 on June 18, 2003.

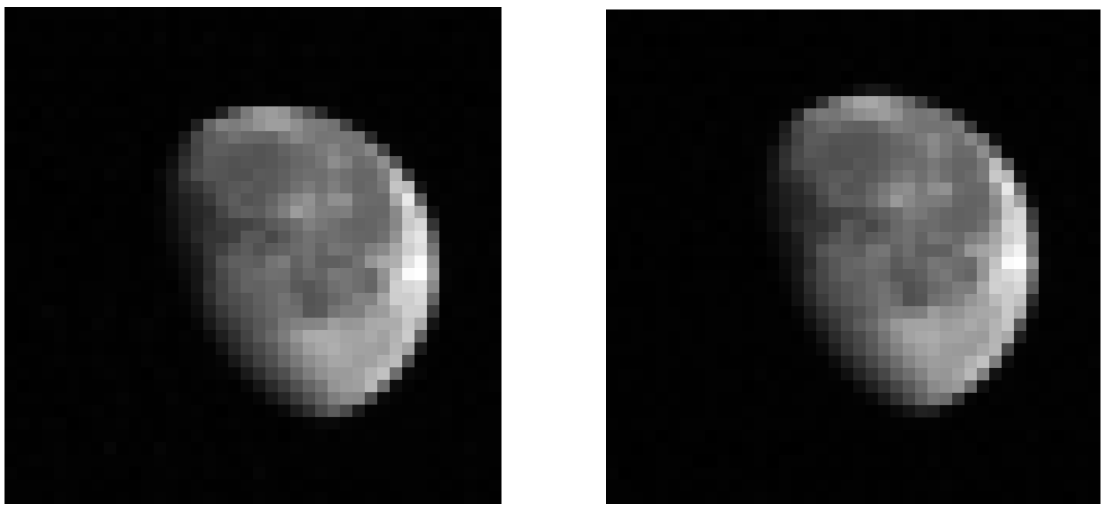

Figure 1. Lunar images observed by Terra MODIS on June 18, 2003. Left: all 40 detectors of B1 within one scan. Right: only middle detector of B1 with multiple scans.

The width of the Moon is approximately 7 pixels of the MODIS 1km bands. We take the center 30 frames (cross-track pixels) of the SV to provide lunar radiance in this analysis. The region is about four times larger than the size of the Moon. Beyond the region, the measured Digital Number (DN) corresponds to response of the background. The DNs of the adjacent 5 frames of the region at each side are averaged to provide the averaged background Digital Number $\overline{DN_{bg}}$. Then the background subtracted digital number of a lunar view is evaluated by

$$dn(N,S,F,D,B) = DN(N,S,F,D,B) - \overline{DN_{bg}(N,S,D,B)} \tag{1}$$

where N, S, F, D, and B represent scan number, subframe, frame, detector, and band, respectively, and the corresponding lunar radiance can be expressed as

$$L(N,S,F,D,B) = dn(N,S,F,D,B)m_1(B,D,S,M_N) / RVS(B,M_N,F), \tag{2}$$

where $m_1(B,D,S,M_N)$ is the calibration coefficient and $RVS(B,M_N,F)$ is the response versus scan angle, and M_N denotes the scan mirror side of the *N*th scan.

For BBR along the scan direction, we sum the total lunar radiance for a given frame in each band

$$S(F,B) = \sum_{D,S,N} L(N,S,F,D,B). \tag{3}$$

We can further normalize the lunar radiance over frames and get

$$s(F,B) = S(F,B) / \sum_F S(F,B). \tag{4}$$

For any two MODIS bands, B_i and B_j, we can always define

$$U_{B_i,B_j}(x)=\sum_F\{s(F,B_i)-[s(F+floor(x),B_j)$$
$$\times(1+floor(x)-x)+s(F+1+floor(x),B_j) \tag{5}$$
$$\times(x-floor(x))]\}^2,$$

where function *floor(x)* yields the closest integer less than or equal to *x*. If $s(F,B_i)$ is identical to $s(F,B_j)$, $U_{B_iB_j}(x)$ approaches its minimum at $x=0$. Let $x_{\min}^{B_iB_j}$ be the value of *x* at which $U_{B_iB_j}(x)$ has its minimum value. Then the BBR for detector B_i relative to B_j along the scan direction is given by

$$\Delta_{B_iB_j}=x_{\min}^{B_iB_j}-(0.5/S_{B_j}-0.5/S_{B_i}), \tag{6}$$

where S_B denotes the total number of subframes of band B. The MODIS detectors are aligned at the beginning of each frame while the digital numbers are taken at the middle of each frame or subframe. The second term in Eq.(6) accounts for the effects due to different number of subframes in B_i and B_j. With exactly the same approach, we can calculate $x_{\min}^{D_iD_j}$ for the detectors belonging to the same band B. The DDR among them can then be calculated by

$$\Delta_{D_i,D_j}=x_{\min}^{D_iD_j}-1.447(D_j-D_i)/(S_Bf_{os})$$
$$\times\mathbf{v}_{moon}\bullet(\mathbf{v}_{MODIS}\times\mathbf{p}_{MODIS})/(v_{MODIS}p_{MODIS}s_{moon}), \tag{7}$$

where f_{os} is oversampling factor for 1km bands, s_{moon} is the pixel size of the MODIS 1km bands on lunar surface, and $\mathbf{v}_{moon}$, $\mathbf{v}_{MODIS}$, $\mathbf{p}_{MODIS}$ are vectors of, velocity of the Moon, the velocity of the MODIS, and the position of the MODIS, respectively. The second term in Eq.(7) removes the effect of the movement of the Moon along the scan direction.

For BBR along the track direction, we sum over the total lunar radiance with same scan number for each band

$$T(N,B)=\sum_{D,S,F}L(N,S,F,D,B). \tag{8}$$

Same as for frame, we further normalize the lunar radiance over scans and get

$$t(N,B)=T(N,B)/\sum_N T(N,B). \tag{9}$$

For any two MODIS bands, B_i and B_j, we define

$$V_{B_i,B_j}(y)=\sum_N\{t(N,B_i)-[t(N+floor(y),B_j)$$
$$\times(1+floor(y)-y)+t(N+1+floor(y),B_j) \tag{10}$$
$$\times(y-floor(y))]\}^2.$$

Let $y_{\min}^{B_iB_j}$ be the value of *y*, at which $V_{B_i,B_j}(y)$ reaches its minimum. Then the BBR for B_i relative to B_j along the track direction is given by

$$\Delta_{B_iB_j}=y_{\min}^{B_iB_j}\ /\ f_{os}. \tag{11}$$

Same as for DDR along the scan direction, we can calculate the DDR along the track direction for detectors belonging to the same band *B*

$$\Delta_{D_iD_j}=y_{\min}^{D_iD_j}\ /\ f_{os}\ +(D_j-D_i)/S_B, \tag{12}$$

where the second term accounts for the designed detector shift.

3. RESULTS AND COMPARISON

The moon has been used to monitor both Terra and Aqua MODIS radiometric stability for the reflective solar bands. They both view the Moon approximately monthly with the Sun-Moon-MODIS phase angle in the region [55°, 56°]. A spacecraft roll maneuver is usually implemented for each lunar calibration to keep the phase angle in the confined region. Within the phase angle region, the detectors of bands B13, B13h, B14, B14h, B15, and B16 of both instruments are saturated. Thus, the BBR of these bands cannot be derived from the lunar data. The BBR of the SWIR bands B5, B7, B7, and B26 should not be derived from the lunar data because of the SWIR cross-talk which are amplified in lunar observations since the lunar temperature is much higher than that of the Earth surface. In the following, we will focus on B1-B4, B8-B12, and B17-B19.

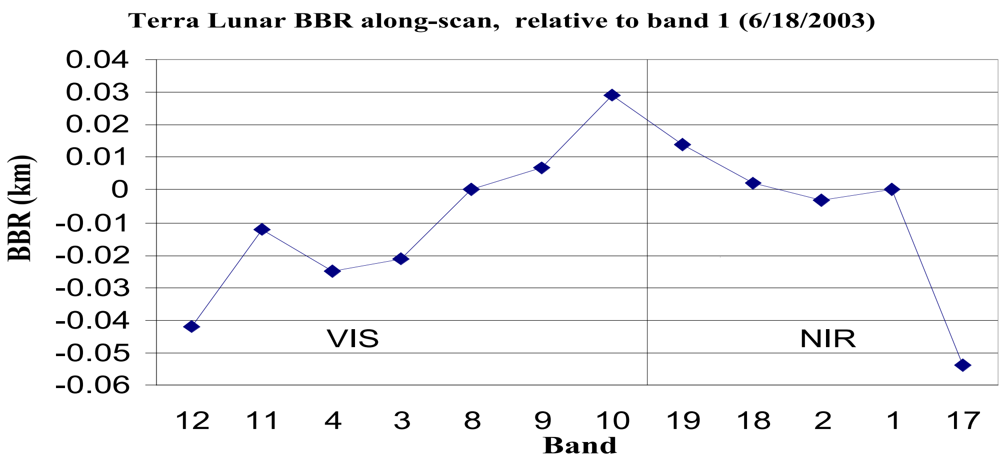

Figure 2. Current (6/18/2003) BBR along the scan direction.

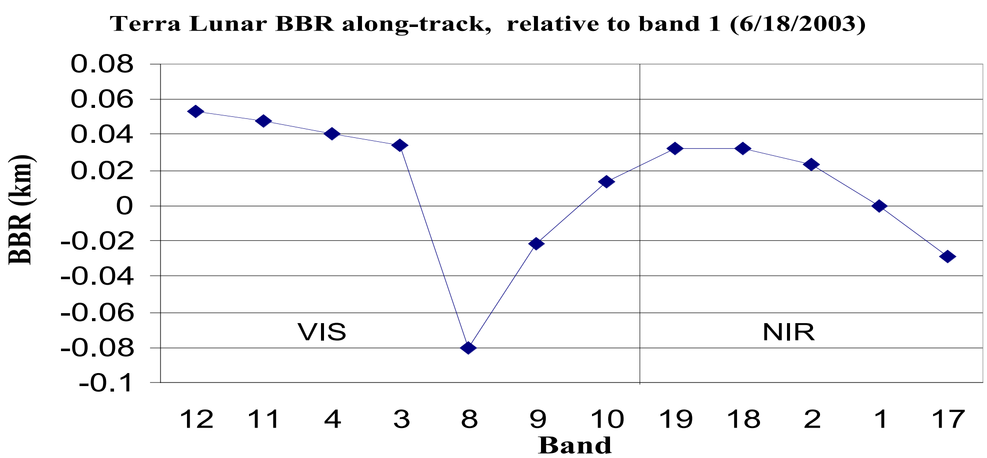

Figure 3. Current (6/18/2003) BBR along the track direction.

Figures 2 and 3 show the current BBR along the scan and track directions, respectively, for Terra B1-B4, B8-B12, and B17-B19 with B1 as the reference band. They are calculated with the lunar data observed on June 18, 2003. The abscissa in both figures is the band number in location sequence on the Focal Plane Assembly (FPA). The BBR along the scan direction in Figure 2 varies from –0.06 to 0.03km. It is shown that B2, B8, B9, and B18 are very well registered relative to B1 in the scan direction. The BBR along the track direction in Figure 3 ranges from –0.08 to 0.05km. The result shows that B8 on the VIS FPA has largest shift along the track direction relative to B1.

Terra MODIS has been on-orbit for three and one-half years. More than thirty lunar observations have been implemented for Terra MODIS. The solid curves in Figures 4 and 5 show the variation of the BBR of Terra MODIS along the scan direction in the past three and one-half years, where B1 is the reference band and a minus sign has been applied for the convenience of the comparison with those derived from SRCA spatial mode data later. The averaged BBR of the VIS bands ranges from –0.05 to 0.05km. For each band, the BBR has a yearly oscillation. The amplitudes of the oscillation are about 0.05km for all VIS bands. The averaged BBR of the NIR bands ranges also from –0.05 to 0.05km. As with those of VIS bands, the BBR of each NIR band also has a yearly oscillation pattern. The oscillation amplitudes of B17 and B19 are larger than those of VIS bands but that of B2 is much smaller. We are still investigating the causes of the yearly oscillation pattern in the figures.

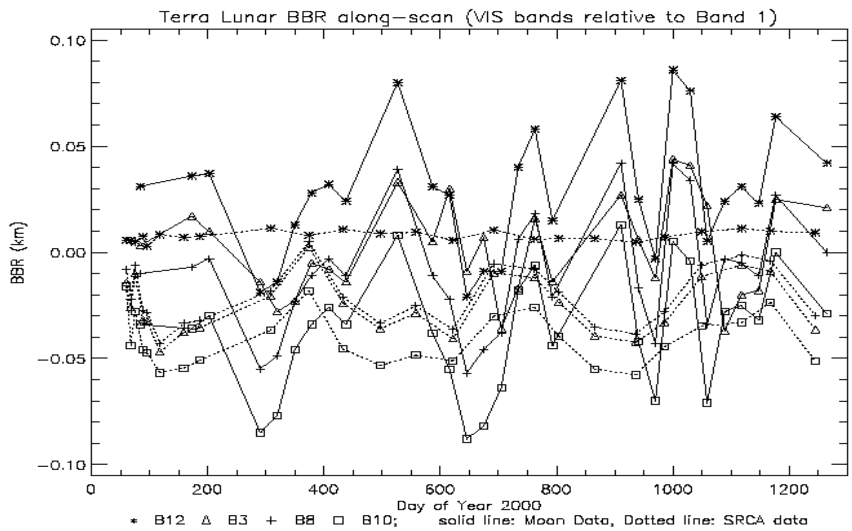

Figure 4. BBR of Terra VIS bands along the scan direction.

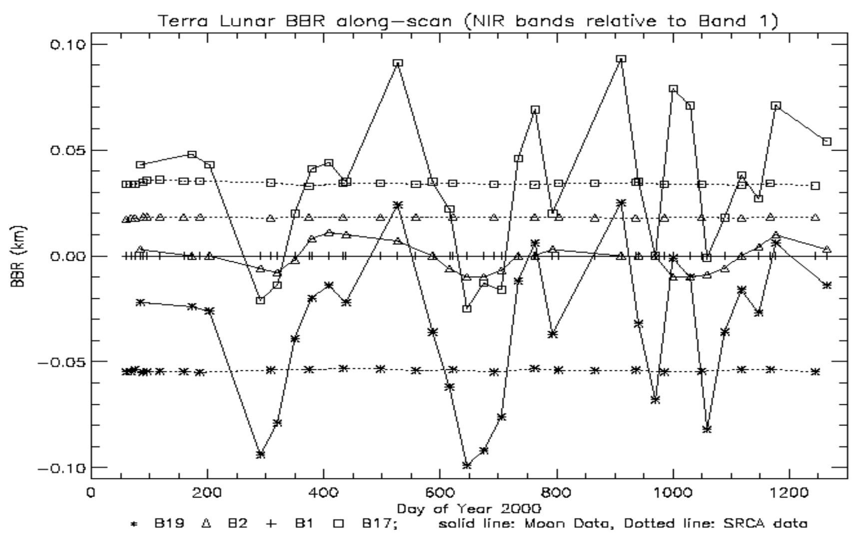

Figure 5. BBR of Terra NIR bands along the scan direction.

The spatial characterization of the MODIS is performed on-orbit by the SRCA. The dashed curves in Figures 4 and 5 are the BBR along the scan of Terra VIS and NIR bands, which are derived from the SRCA spatial mode data. The SRCA BBR along the scan is defined in opposite direction of the lunar BBR given in Eq.(6). The SRCA measurement of spatial mode is implemented once every two months for both Terra and Aqua MODIS. For VIS bands, both lunar and SRCA BBR have a yearly oscillation pattern, except SRCA BBR of B12. The oscillation amplitudes of the lunar BBR are larger than those of SRCA BBR. For each year, the lunar BBR of each band has two peaks while the corresponding SRCA BBR has only one peak. For each NIR band, SRCA BBR has no yearly oscillation pattern while lunar BBR does. Except for the yearly oscillation in lunar BBR, the two sets of BBR are in good agreement for all VIS and NIR bands.

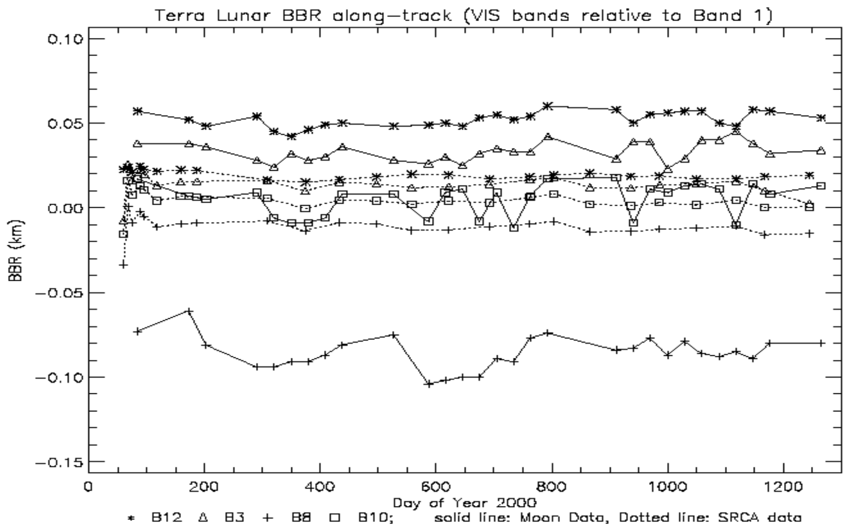

Figure 6. BBR of Terra VIS bands along the track direction.

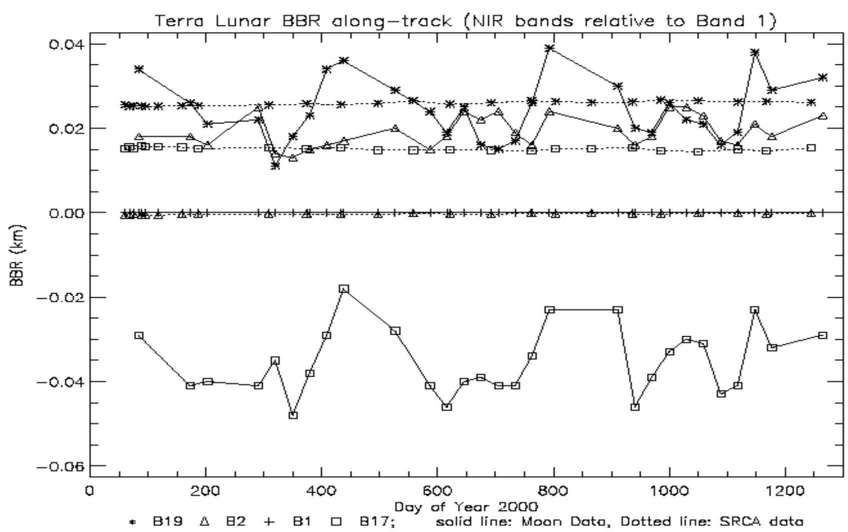

Figure 7. BBR of Terra NIR bands along the track direction.

Lunar BBR of Terra MODIS VIS along the track direction is shown in Figures 6 and 7 with solid curves. Again the reference band is B1. The lunar BBR of VIS bands varies from –0.10 to 0.05km. B8 has largest BBR among VIS bands and has opposite sign compared to other bands. The lunar BBR of NIR bands ranges from –0.04 to 0.03km. The yearly oscillation pattern can still be observed in lunar BBR along the track direction but the amplitudes of the oscillations are much smaller than those observed in lunar BBR along the scan direction. The dotted lines in Figures 6 and 7 represent SRCA BBR. They are very smooth over time. The two sets of BBR match very well within their evaluation uncertainty limit, except B8 and B17. The differences of the two sets of BBR for B8 and B17 are about 0.08km and 0.05km, respectively.

Using Eq.(7) and Eq.(12), we can calculate relative DDR along the scan and along track directions, respectively, for detectors belonging to the same band. Figure 8 shows the BBR of the detectors of Terra MODIS B8 along the scan direction, where the reference detector is D1. The BBR varies from -0.13 to 0.01km. It is seen clearly that there is pattern of a yearly oscillation with two peaks. Figure 9 shows the corresponding DDR along the track direction. A similar oscillation pattern is also seen in the along-track DDR of the detectors. The BBR along the track direction varies from –0.02 to 0.04km. The variation is smaller than that of BBR along the scan direction.

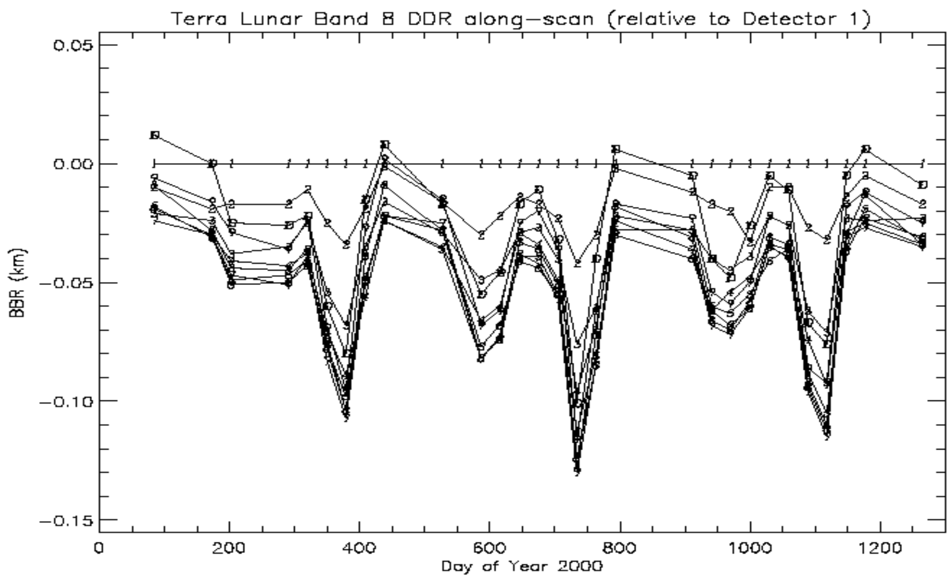

Figure 8. DDR of Terra MODIS B8 along the scan direction.

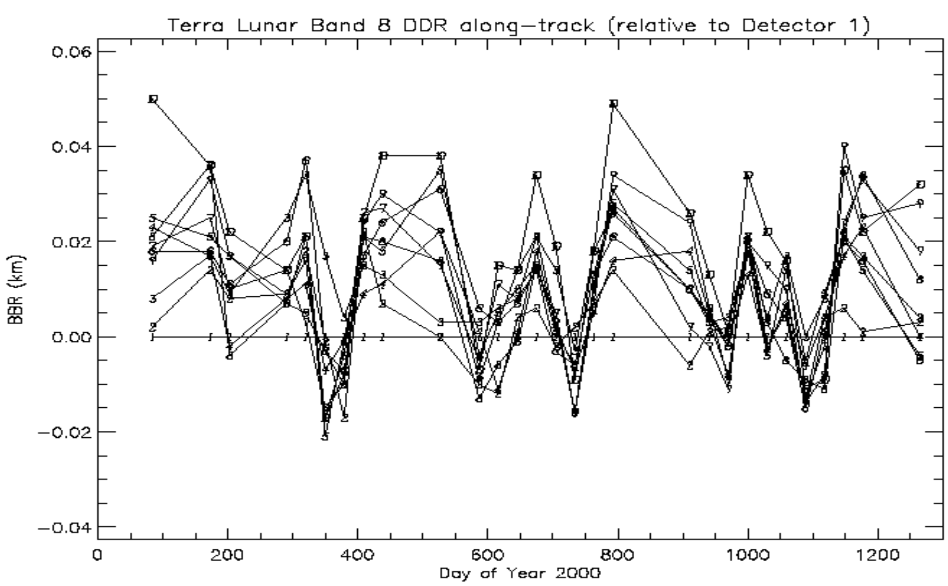

Figure 9. DDR of Terra MODIS B8 along the track direction.

4. SUMMARY

We have developed an algorithm to monitor the spatial characteristics of the MODIS reflective solar bands using lunar observations. The method enables us to calculate the BBR of the MODIS instrument both along the scan and track directions. With the method, we can calculate relative BBR for any two given bands as long as they are not saturated. We can also calculate the DDR for any given detectors in the same band. The method has been applied to both Terra and Aqua MODIS. The results show that the BBR derived from lunar data with the method are quite consistent. They also match the SRCA BBR quite well within the evaluation uncertainty limits. A yearly oscillation pattern is observed in lunar BBR. Further investigation of this feature is ongoing.

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